Autonomous Wide Aperture Cluster for Surveillance (AWACS): Adaptive Sampling and Search Using Predictive Models with Coupled Data Assimilation and Feedback

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LONG-TERM GOALS

This research aims to develop and evaluate new environmental-acoustical adaptive sampling and search methodologies, and improve the modeling of ocean dynamics, for the environments in which the main AWACS-06, -07 and -09 experiments will occur, using the re-configurable REMUS cluster and coupled data assimilation.

OBJECTIVES

Specific objectives are to:

i) Evaluate current methods and develop new algorithms for adaptive environmental-acoustical sampling, search and coupled data assimilation techniques (Stage 1), based on a re-configurable REMUS cluster and on idealized and realistic simulations (with NPS/OASIS/Duke)

ii) Research optimal REMUS configurations for the sampling of interactions of the oceanic mesoscale with inertial oscillations, internal tides and boundary layers (with WHOI/NPS/OASIS)

iii) Improve models of (sub)-mesoscale ocean physics and develop new adaptive ocean model parameterizations for specific regional AWACS-06, -07 and -09 processes. Study and compare processes/dynamics in these regions (with WHOI)

iv) Provide near real-time fields and uncertainties in AWACS-06, -07 and -09 experiments and, in the final 2 years, develop algorithms for fully-coupled physical-acoustical data assimilation among relocatable nested 3D physical and 2D acoustical domains (with NPS)

v) Provide adaptive sampling guidance for array performance and surveillance (Stage 2), and link our MIT research with vehicle models and command and control.

APPROACH

The project is founded on a build-test-build approach, with evaluations at sea. The basic research formulates and tests hypotheses and new methodologies. Idealized and realistic data-driven simulations are utilized. Scientific investigations, development of methods and algorithms, and design of AWACS components are ongoing throughout the program, based on at-sea exercises and post-test analyses.

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14. ABSTRACT
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The technical research involve: (i) develop environmental-acoustical adaptive sampling and search schemes; (ii) evaluate and improve models and parameterizations of (sub)-mesoscale processes, based on model-data comparisons and data assimilation; and (iii) develop new adaptive parameterizations in ocean models. The Error Subspace Statistical Estimation (ESSE) system is employed and improved for coupled data assimilation. For ensemble predictions, it utilizes models such as the primitive equation model of the Harvard Ocean Prediction System (HOPS) and the coupled normal-mode acoustic propagation model of the Naval Postgraduate School. During AWACS exercises, (near) real-time environmental field predictions and coupled physical-acoustical adaptive sampling and search recommendations are provided. In FY08-09, algorithms and software for advanced high-resolution physical-acoustical data assimilation (DA) are developed. This involves relocatable nested domains and full feedbacks among sets of nested 3D ocean fields and nested 2D acoustic sections.

The PI and his MIT group are working on collaborative efforts that involve interdisciplinary, multi-scale ocean science and modeling, coupled data assimilation, adaptive sampling and search, adaptive data-driven modeling, multi-model Bayesian estimation, and control theory and optimization. The preparation for, and participation to, the AWACS at-sea experiments (2006, 2007, 2008 and 2009) benefit from these other related efforts. Significant components of the AWACS work carried out so far are illustrated in http://mseas.mit.edu/Research/AWACS/index.html.

WORK COMPLETED

1. Nested Free-Surface Primitive Equation Simulations

We investigated new nesting schemes and open boundary conditions to improve the quality of our free-surface PE simulations. Such research is necessary since no much as been done on telescopic nesting with free-surfaces. To do so, a stripped-down idealized test case was set-up to isolate potential issues in the nesting algorithm from other effects (see Figure 1). Specifically, an idealized current with Gulf Stream characteristics was placed in a flat-bottomed periodic channel. The solid boundary north and south wall, along with the periodicity in the east-west direction, eliminated possible effects from open boundaries. The flat bottom removed any effects from topography. The simulations were unforced, eliminating interactions with atmospheric forcing and tides. In the middle of this domain, a small open-boundary domain was nested.

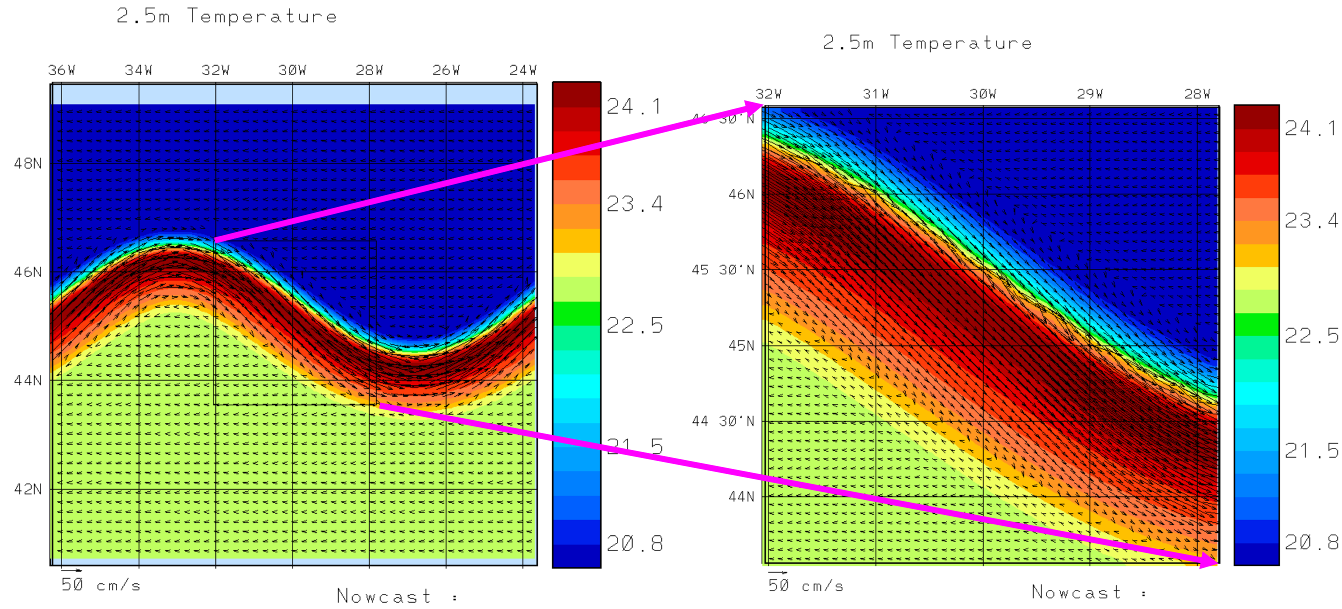

Figure 1. Temperature and velocity in an idealized nesting set-up. Left: periodic channel domain. Right: nested sub-domain.

A series of experiments were performed examining parameter sensitivities and different model formulations (rigid-lid with transport streamfunction as a state variable; rigid-lid with surface pressure and barotropic velocity as state variables; and free surface). In all cases, nested and stand-alone simulations were compared, including the details of the initial time behavior.

2*. **Nested high-resolution generalized inverse estimation of barotropic tides***

A paper was published describing an inverse scheme for the assimilation of observational data into a depth-integrated spectral shallow water tidal model (Logutov and Lermusiaux, 2008). The inverse scheme is implemented by carrying out an optimization in the open boundary condition space rather than in the observational space or model state space.

3*. **Adaptive environmental-acoustic sampling***

A series of meetings were held with K Heaney (OASIS) and T. Duda (WHOI) to design an OSSE to validate a genetic algorithm approach to optimal adaptive sampling. Two sets of “true ocean” fields, representing conditions before (24-27 Aug) and after (4-7 Sep) the passage of tropical storm Ernesto, were provided at 1 hour temporal resolution. From the OSSE results, “true ocean” profiles were generated in each time period modeling three different sampling strategies for a set of 5 gliders: (i) the optimized pattern selected by the genetic algorithm approach; (ii) a uniformly spaced set of transects across the shelf; and, (iii) a random set of initial glider positions constrained by minimum initial separation.

Two papers on adaptive sampling were published. The first paper (Yilmaz et al., 2008) uses Mixed Integer Linear Programming (MILP) to design sampling tracks which maximize forecast uncertainty along the track. The second paper (Wang et al., 2008) consists of a succession of two schemes. Firstly, data assimilative environmental and acoustic propagation ensemble modeling provide input to a scheme which finds parameter values for autonomous sampling behaviors that optimally reduce the forecast of acoustic uncertainty. Secondly, this forecast of optimal autonomous sampling behavior

parameters is modified on situ, onboard of the vehicle in real-time as it samples the ocean. A third paper (Yilmaz and Lermusiaux, 2009) is being finalized. It develops a scheme which selects the optimal sampling path by forecasting the reduction of uncertainties, inserting ESSE error reduction forecasts as part the MILP path planning.

RESULTS

1. Nested Free Surface Primitive Equation Simulations

The idealized test cases exposed the presence of high frequency waves in the free surface that are trapped by the open boundary conditions, for both nested and non-nested open boundaries. These waves are exacerbated in the smaller domain by the proximity of the domain corners to the strong gradients associated to the "Gulf Stream", as illustrated next in Figure 2. However, turning the periodic channel to an open channel produces similar (although weaker) waves in the larger domain. Using a strong filter can ameliorate the effects, but leaves open the question of whether these trapped waves contribute to the long-term drift in the barotropic velocities observed between nested free surface simulations. Current efforts to allow these waves to exit the domains revolve around implementing variations of the Flather boundary conditions, which are designed to permit the radiation of gravity waves.

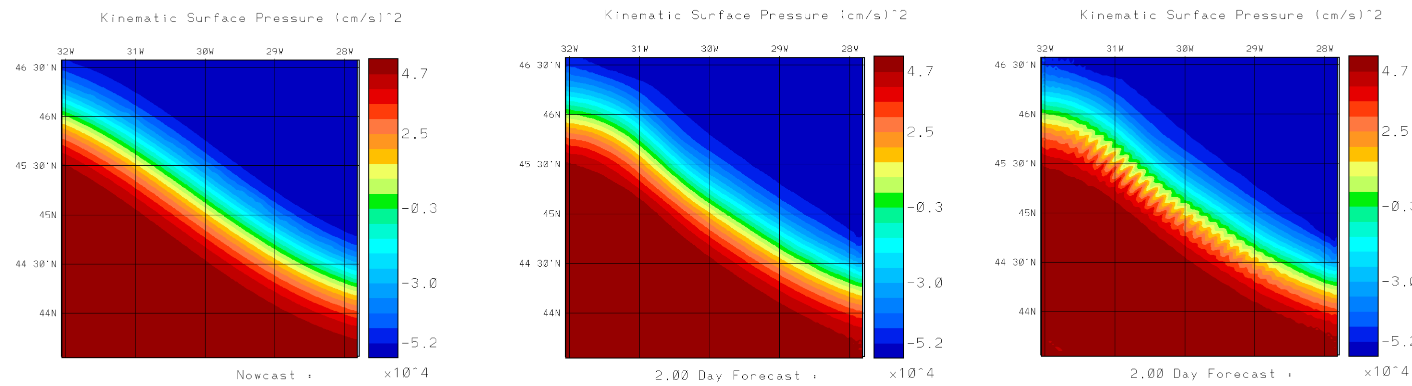

Figure 2. Surface pressure tests. Left: Initial conditions. Middle: 2day rigid-lid forecast. Right: 2day free surface forecast

2. Nested high-resolution generalized inverse estimation of barotropic tides

A methodology and computational system for forward and inverse regional tidal estimation was presented (Logutov and Lermusiaux, 2008). Tidal fields were computed for the PLUSNet PN07 exercise and made available to the AWACS lead (Abbot et al, OASIS) for the joint AWACS-PLUSNet effort. These simulations (illustrated on Figure 3) in the complex Strait of Juan de Fuca / Hood Canal / Dabob Bay region demonstrated both the quality of the forward solution and the important amplitude & phase corrections provided by the inverse solution. The technique of optimizing the data fit in the open boundary space was found to be somewhat more robust than the method of representers.

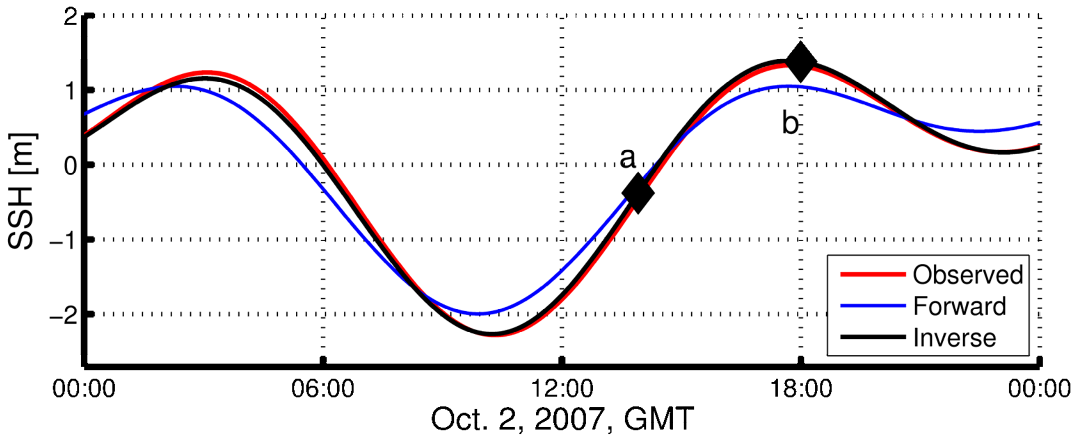

Figure 3. Comparing tidal solutions (blue & black) to the T2 tide gauge data (red) in Hood Canal. Note that (a) this tide gauge was not used in the inverse solution and (b) the phase & amplitude improvement of the inverse solution.

3. Adaptive environmental-acoustic sampling OSSEs

The two-stage approach of Wang et al. (2008) was shown to be computationally feasible. Daily forecasts of environmental fields and uncertainties were used to generate 10 to 20 scenarios for sound speed sections, which were used for acoustic forecasts. ESSE ensembles of acoustic transmission losses and sound speed sections were then used to optimize prior estimates for parameters governing "yo-yo" sampling schemes. The summer daily heating was shown to impact the optimal sampling, as illustrated on Figure 4. In the morning, the optimization chose yo-yo paths to sample the whole water column. In the afternoon, the optimal result was to sample the whole water column on the first trip but to sample the secondary thermocline (due to the afternoon warming of the ocean surface) on the return trip.

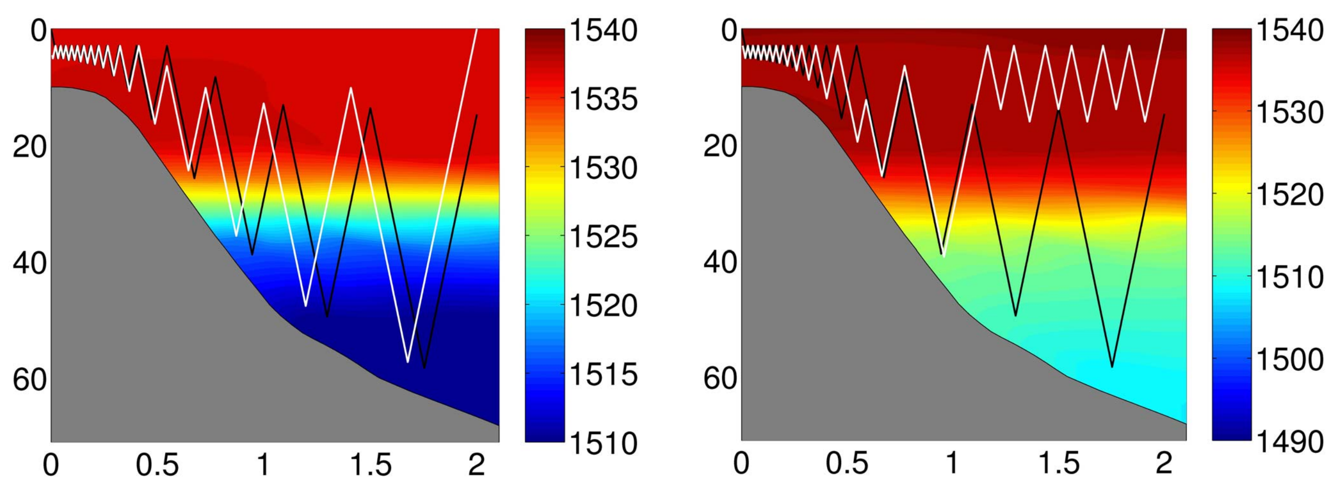

Figure 4. Optimized yo-yo paths for morning (left) and afternoon (right) sampling. Initial path (black) return (white).

The mixed integer linear programming (MILP) method of Yilmaz et al. (2008) was shown to solve the optimization problem for path planning using objective functions based on realistic ocean uncertainty forecasts within allotted time limits. The effects of variations on the type of constraints, number of vehicles and time dependence were studied and diverse sensitivity studies carried out. The general framework of the MILP methodology easily incorporates future extensions. An example is shown on Figure 5.

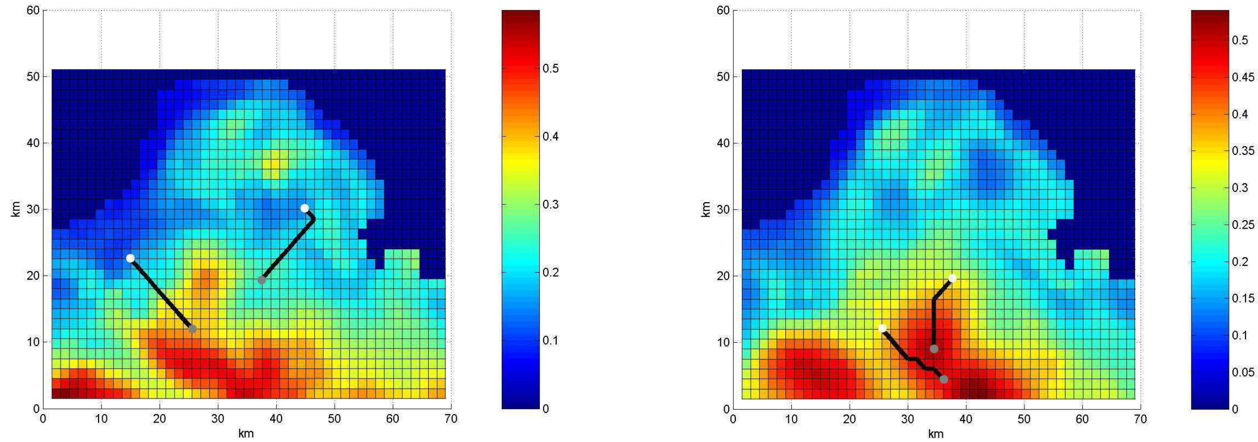

Figure 5. MILP path planning for 2 vehicles with time dependent uncertainty field. Temperature uncertainty fields are shown for day 1 (left) and day 2 (right). Overlain are the sampling paths optimized for the two day for 2 vehicles with each days' starting position in white and terminal position in gray. Note that on day 1, the path on the right samples low uncertainty areas to position the vehicle for sampling very high uncertainty areas on day 2.

IMPACT/APPLICATIONS

Better modeling of ocean dynamics at sub-mesoscales including tidally-driven processes is required for accurate and useful acoustic predictions. Coupled physical-acoustical data assimilation enhances predictive capabilities and allows for estimation feedbacks including adaptive modeling. Novel environmental-acoustical adaptive sampling is essential for efficient autonomous naval surveillance. Other application areas include coastal seas management, homeland security and geophysical sciences.

TRANSITIONS

Data-assimilative HOPS-ESSE re-analyses for the SW06-AWACS (Aug.-Sep. 2006) were transitioned to K. Heaney (OASIS) and Andrew Tremblay/Sylvia Ferrari (Duke) for adaptive sampling studies and to John Joseph (NPS) for ambient noise estimation work.

RELATED PROJECTS

We collaborated with K.D. Heaney (OASIS) and T.F. Duda (WHOI) under an SBIR. Interactions have also occurred with MIT-OE/EAPS (N. Patrikalakis, C. Evangelinos) for adaptive sampling and with OSU (B. Miller) and NRL (A. Warn-Warnas) for physical-acoustical studies and data assimilation.

PUBLICATIONS (2008)

1. Logutov, O.G. and P.F.J. Lermusiaux, 2008. *Inverse barotropic tidal estimation for regional ocean applications*. Ocean Modelling, Vol 25, 17-34. [Published, refereed].
2. Wang, D., P.F.J. Lermusiaux, P.J. Haley, D. Eickstedt, W.G. Leslie and H. Schmidt, 2008. *Acoustically Focused Adaptive Sampling and On-board Routing for Marine Rapid Environmental Assessment*. Journal of Marine Research. [In Press, refereed]
3. Yilmaz N.K., C. Evangelinos, P.F.J. Lermusiaux and N. Patrikalakis, 2008. *Path Planning of Autonomous Underwater Vehicles for Adaptive Sampling Using Mixed Integer Linear Programming*. IEEE Ocean Engineering. [In Press, refereed].

Figures, presentations and other publications are available from: http://mseas.mit.edu/ and http://mseas.mit.edu/Research/AWACS/index.html. All documents are available upon request.